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Turbine Erosion Research in Great Britain

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ABSTRACT

The variables influencing erosion in wet-vapor turbines are identified and discussed in this Memorandum. Information is presented that was obtained from a visit to research installations in Great Britain during October of 1965. The applicability of this information to the formulation of an analytical model of erosion in liquid-metal vapor turbines is indicated. Phenomena for which results are given are moisture formation, moisture collection, droplet shedding, droplet breakup, liquid impact, and material removal. Analytical expressions are indicated for moisture formation, moisture collection, droplet breakup, and liquid impact. Experimental results for droplet shedding and material removal are summarized. The sizable scatter of experimental data from material removal experiments and the lack of sufficiently accurate liquid-metal property data will limit the accuracy of the analytical model to be formulated.

I. INTRODUCTION

Several government sponsored research programs are currently oriented toward developing a technology for alkali metal vapor turbines. Power systems using these components are contemplated for the post-1970 period when power requirements should be in the multi-hundred kw range either for missions using electric propulsion or for auxiliary power. In order to attain high cycle efficiencies and low system weights, such turbines will have several expansion stages. The low pressure stages will operate in the wet-vapor regime and, as a consequence, blade erosion and performance losses due to liquid impact may occur. Unfortunately, the information presently available on erosion in liquid-metal vapor turbines is inadequate for design of reliable units. For this reason, two programs on the subject of erosion in potassium vapor turbines were initiated by NASA Office of Advanced Research and Technology (OART). These investigations[1] are currently being directed by JPL.

Although the problem of blade erosion in steam turbines has been attacked for many years, it still exists. The past approach has been to decrease erosion by using harder blade materials or facings and by removing moisture. This method has given satisfactory results for moderate tip-speeds. However, the attainment of higher tip-speeds and lower quality steam in some modern units have demanded a more fundamental understanding of the factors influencing erosion. For this reason, there

[1]Carried out under Contracts NAS 7-390 and NAS 7-391.

has arisen in Great Britain a significant research effort including the fields of moisture formation, moisture collection, droplet shedding, droplet breakup, droplet impact, and material removal. By comparison, the efforts in these fields in the United States have been quite modest. Because the value to the potassium programs of the British work with steam was apparent, the author visited the appropriate research installations during 25 to 29 October 1965. Table 1 summarizes the laboratories visited and lists personnel contacted, together with their areas of technical interest. The following Report, in addition to presenting the information exchanged, applies the findings to the problem of erosion caused by liquid metal impact.

Table 1. Laboratories and personnel visited

Laboratory	Location	Persons contacted	Technical areas discussed
Marchwood Engineering Laboratory	Southampton, England	J. L. Eaton D. Pearson	Erosion test results Material removal mechanisms Liquid impact pressures
Central Electricity Research Laboratory	Leatherhead, Surrey, England	D. G. Christie G. C. Gardner M. Moore K. H. Jolliffe	Droplet formation and collection Droplet shedding and breakup Impact damage mechanisms Crystalline damage effects Instrumentation
Cavendish Laboratory	Cambridge, England	J. E. Field J. H. Brunton G. P. Thomas M. J. Wilson	Liquid impact pressure Impact damage mechanisms Surface influence on damage Material removal mechanisms
National Engineering Laboratory	East Kilbride, Scotland	J. M. Hobbs D. T. Jamieson	Erosion and cavitation test results Surface influence on damage Accommodation coefficient for condensation

II. MOISTURE FORMATION

That sub micron droplets are formed in vapor during the expansion process appears to be one of the least controversial subjects of turbine erosion. The consensus at the Central Electricity Research Laboratory (CERL) was that Gyarmathy's (Ref. 1) treatment of this phenomenon was adequate and could be extended to liquid metal vapors, providing the proper values of fluid properties were known. The results of his calculations have been validated by his tests at Brown Bovari (Ref. 2) and are in general agreement with other work. Probably the most important point made in Gyarmathy's thesis is that performance loss due to moisture—and, hence, to erosion—can be reduced if the reversion point (Wilson line) occurs in a region of high pressure gradient. The location of the reversion point in a high pressure gradient reduces the size of the condensation droplets. The formation of smaller droplets in the flow reduces the amount of moisture collected and, subsequently, shed in damaging form from the stator blades. It is believed at both CERL and Marchwood that control of this initial droplet size is a promising technique for reducing erosion damage.

The actual thermodynamic location of the Wilson line for potassium vapor is not presently known. However, cloud chamber experiments have been conducted for other polymer vapors (Ref. 3), and future tests with potassium are planned.

The possibility also exists that the geometric location of the reversion point can be fixed by the creation of artificial condensation nuclei by the introduction of ionizing radiation or electric fields. Control of the initial droplet size through this mechanism is a design technique that should be considered for reducing potassium turbine erosion. Small-scale steam turbine tests could probably establish the validity of this approach and determination whether or not sufficient artificial nuclei can be introduced to fix the location of the reversion point.

III. MOISTURE COLLECTION

The collection of the sub-micron condensation droplets on both static and moving surfaces in the turbine is a subject of considerably more controversy. Gardner maintains that, depending on the droplet size, the collection is due either to eddy diffusion or to Brownian movement. Gyarmathy, on the other hand, considers centrifugal forces on the droplets in the free stream to be the sole mechanism responsible for the collection. For the example in Gardner's paper (Ref. 4), these differing assumptions give approximately the same answer. However, for other sizes of condensation droplets, the predicted collection rate can differ by more than an order of magnitude (as would the predicted erosion rate). Moreover, Gardner's model shows a minimum collection rate as a function of droplet diameter. Below this diameter, Brownian movement is more important than eddy diffusion, and collection increases as size decreases. This result, if valid, would place a lower limit on the effectiveness of any scheme to reduce the size of droplets formed in the condensation process. Two factors support the use of Gyarmathy's equations:

1. His predictions for performance loss due to moisture are in general agreement with the standard empirical rule of $\sim \frac{1}{2}\%$ efficiency loss for every 1% of moisture.

2. His equations are based on potential flow and empirical relations for impact separators. Since, according to Gardner, the boundary-layer displacement thickness is on the order of 1 to 5% of the channel width, it would seem that potential flow calculations may be justified.

The main uncertainty in Gyarmathy's calculation is the influence of free-stream turbulence from upstream stages. Gardner agrees that one possible method of resolving which model is correct would be to conduct cascade tests where the blade curvature is systematically varied and moisture collection is measured optically. In this test, the droplets would have to be produced by an upstream turbine to be in the proper size range.

In the absence of any other information, the above reasons would probably favor use of Gyarmathy's equations at this time.

IV. DROPLET SHEDDING AND BREAKUP

Once the moisture has been collected on the stator blades, it has an opportunity to coalesce into larger liquid masses. When droplets are subsequently shed, they are much larger than the condensation droplets and can produce considerable damage when impacted by the moving blades.

A. Detachment

Motion pictures taken at CERL in an operating turbine and in a cascade show droplet sizes of 150 to 1500 μ, which are much larger than condensation droplets ($< 1\ \mu$).

The pictures at CERL were taken at both normal (16 frames/sec) and high speed (8000 frames/sec). These films clearly show the processes of droplet and film growth, detachment, and acceleration. However, the quantitative results obtained may have been influenced by the specific blade design to the extent that they are not representative of what occurs in a well designed turbine. Figure 1 is a sketch of the blade geometry being tested, and of the areas of droplet and film attachment. The abrupt changes in profile and the blunt trailing edge clearly cause substantial flow separation with attendant low-velocity wakes. The low-velocity regions provide locations for the droplets to coalesce and grow to large sizes before being detached from the blade.

The very interesting process of detachment might be amenable to analysis. The following steps can be seen in the films of the trailing-edge droplets (shown in Fig. 2).

1. A droplet grows to a size that is about equal to the trailing-edge thickness of the blade, itself.
2. Bernoulli and drag forces occur when the liquid mass grows larger than the wake region and is subjected to a higher vapor velocity.
3. The above forces cause a flow in the direction of the free vapor stream.
4. Surface tension causes the drop to recover and reverse flow.
5. Oscillations are thus set up that grow in amplitude until the surface-tension force is not sufficient for recovery and the tip of the droplet strips off, forming several smaller droplets.

The oscillations were very regular and appeared to have a period of about 2 to 3 msec for the flow conditions tested. No analytical treatment of this problem is

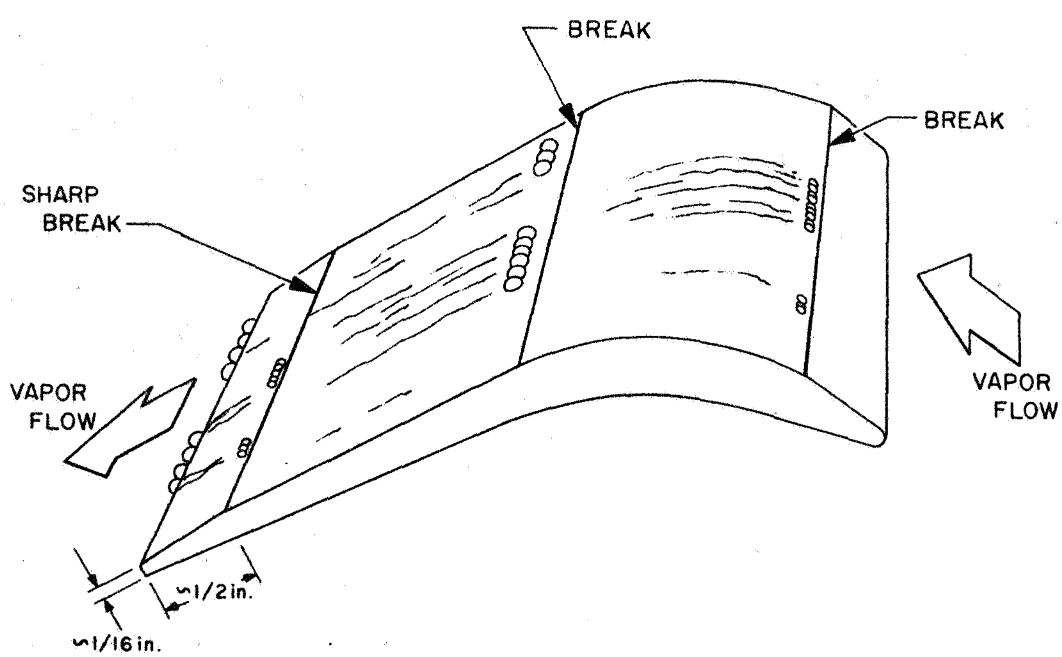


Fig. 1. Nozzle blade tested in CERL steam tunnel, showing areas of attachment and design features

PERIOD OF OSCILLATIONS ≈ 2 TO 3 msec
~5 TO 10 DROPLETS SHED FOR EACH CYCLE
~5 TO 10 OSCILLATIONS / CYCLE
VAPOR VELOCITY 700 TO 1000 ft/sec
DROPLET SIZE 360 TO 1700 μ
NON-WETTING OF SOLID SURFACES BY DROPLETS

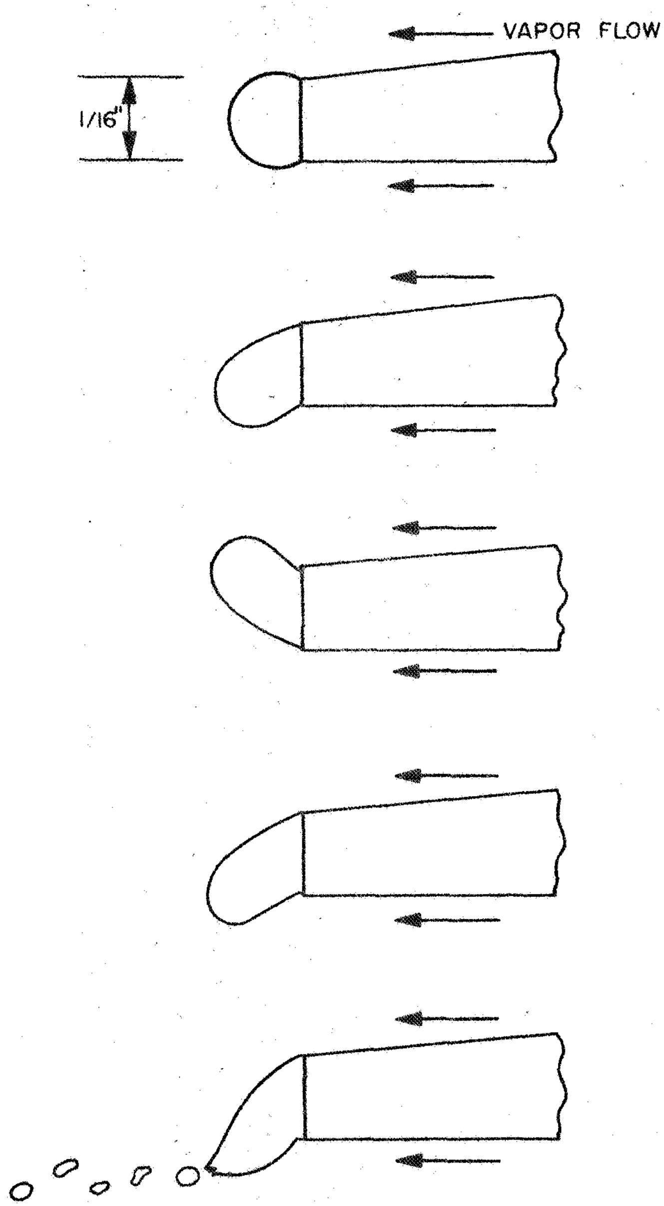


Fig. 2. Observed stages in droplet shedding process from trailing edge of nozzle blade

currently available. If it were, additional information about the velocity field would probably be required before a useful estimate of the detachment size could be made.

The locations of droplets and rivulets in an operating turbine are shown in Fig. 3. This drawing was made at CERL from films taken of the stator through the last row of rotating blades. The maximum diameter of the droplets upon detachment was approximately 400 μ, which is large enough to cause considerable damage. Once again, evidence exists of marked secondary flow and wake effects. Stationary droplets exist on both the trailing edge and on the convex blade surface. The heavy flow from the corner of the nozzle responsible for blade notching is clearly evident in these pictures.

The moisture collected on the stator blades in the steam tunnel was produced by upstream injection. The injected moisture particles (which have a size range of 20 to 50 μ) have been observed, in streak photographs, to rebound from the blade surface. Christie, of CERL, believes this secondary stream of large droplets has little influence on the actual shedding process. This conclusion is partially supported by the similarity of the departing droplets to those observed in a rotating turbine. However, future tests will be conducted by CERL with moisture injection through the blade surface, itself.

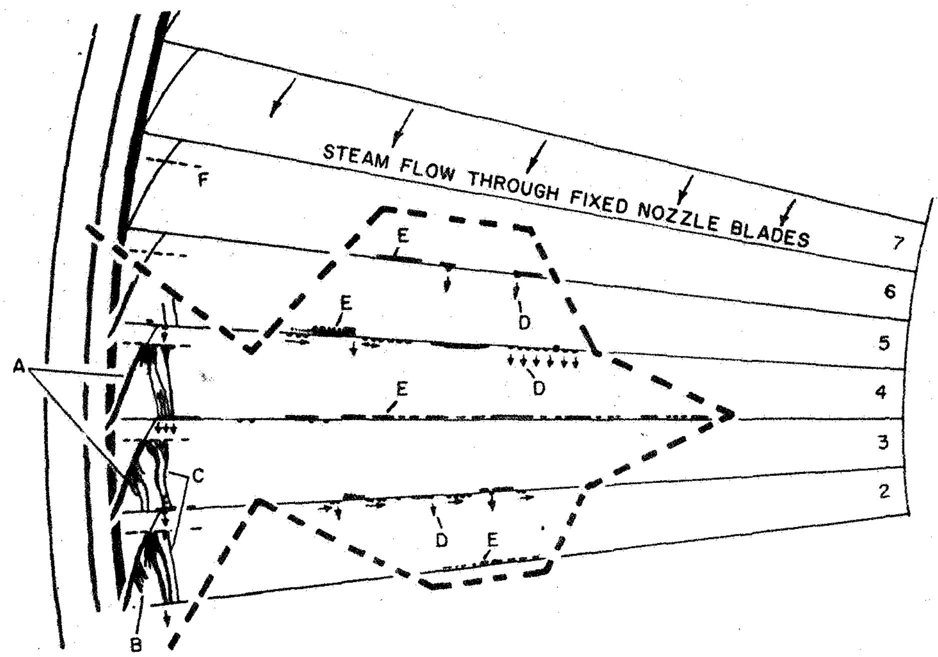
The consensus at CERL seemed to be that a marked improvement in both the size of droplets shed, and the subsequent stream breakup process, could be attained by improved blade design. The contours should be carefully controlled to give pressure gradients and turning angles that will avoid separation. This conclusion is confirmed by Stahl's results (Ref. 5) and should be given careful consideration in the design of the wet-vapor turbine.

B. Breakup

Once the stator droplets are detached and exposed to the freestream or wake velocity, the opportunity exists for an additional size reduction due to breakup. However, the breakup requires a finite time, which may be longer than the time for the droplet to transverse the distance from the stator to the rotating blade. High speed motion pictures, ~ 2×10^6 frames/sec, and streak photographs have been used at CERL to provide information on the droplet acceleration process.

Figure 4 is a plot of droplet velocity, at a fixed distance from the stator blade in the steam tunnel, as a function of droplet size.

The velocity shown is the freestream velocity—which, of course, may be very different from the local wake velocity to which the droplet is exposed. The curves show a velocity and pressure (vapor density) effect that would



A–WATER STREAMS IN CORNER OF NOZZLE
B–FLOW INSTABILITY CAUSING BREAKAWAY OF WATER A
C–WATER CONCENTRATED BY SECONDARY FLOW IN NOZZLE
D–WATER DROPS SHEDDING AT PREFERRED POSITIONS (VERTICAL ARROWS)
E–AREA OF FLOW SEPARATION CONTAINING WATER
F–UP STREAM LIMIT OF VIEW DUE TO INCLINATION OF PERISCOPE
HORIZONTAL ARROWS INDICATE DIRECTION OF MOVEMENT OF WATER DROPS

Fig. 3. Sector of last low-pressure diaphragm showing sources of erosion-producing water drops on the downstream convex face and outlet edge of fixed nozzle blades 2 to 6 (after CERL)

be expected. Higher values of vapor velocity and density generally result in more rapid acceleration of the liquid droplets. Also, smaller droplets are accelerated at a higher rate than are larger droplets. The excessive scatter and the apparently anomalous trends were probably due to variations in spatial location of the shed droplets that changed the value of local vapor velocity to which they were exposed. The results of Fig. 4 could prove useful by enabling calculation of the wake velocity, which would be required to produce the measured droplet velocity. This wake velocity might then be related to the observed diameters of shed droplets to gain insight into the shedding process and be used to provide estimates of the droplet residence time.

The time required for breakup is usually obtained by taking the shorter of the times calculated for breakup, considering the *bag-bursting mechanism* or *Taylor stripping mechanism* (Refs. 5, 6). Gardner feels that the results for both breakup time and final diameter obtained in this way are adequate, provided the wake velocity is known. As examples of the values of break times calculated, Gardner presents the following:

Steam velocity	1200 ft/sec
Steam specific volume	200 ft^3/lb
Droplet initial size	200 μ
Critical diameter	100 μ
Breakup time for bag-bursting mechanism	1.84×10^{-3} sec
Breakup time for Taylor stripping mechanism	0.41×10^{-3} sec

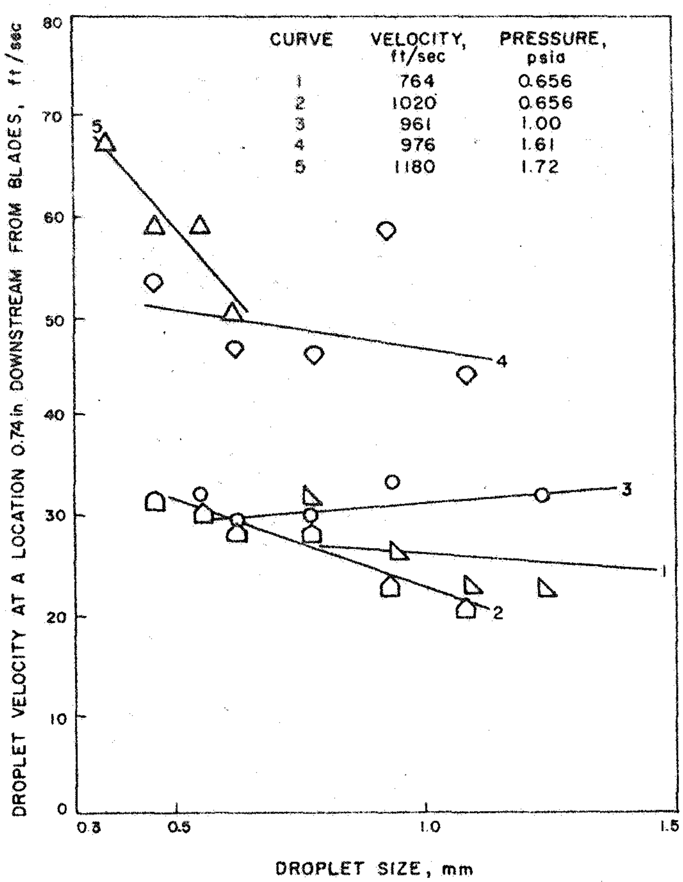


Fig. 4. Droplet velocity vs droplet size at a location downstream from stator blades in a wet steam tunnel (after CERL)

Thus, for this example, the Taylor stripping mechanism would predominate. The equations and assumptions used to obtain these results are discussed in detail in Gardner's paper (Ref. 4).

The optics system installed in the operating steam turbine has also been used to obtain Xenon flash photographs of droplets arriving at the rotating blades. The maximum diameter observed was 450 μ which is about the same value as the maximum size shed. This indicates little or no breakup is occurring in the interval between the droplets leaving the stator and arriving at the rotor blades. Certainly this size is significantly greater than the critical size of 100 μ calculated by Gardner for the freestream velocity. Since the calculated time for breakup is less than the residence time, the larger droplets are probably traveling in wake regions that persist over the entire gap. Analysis of these pictures gave the results recorded in Table 2.

Table 2. Droplets arriving at rotating blades

Erosion parameter	Turbine load		
	100%	60%	40%
Drops/hr/unit-area reaching last stage $\times 10^6$	4.2	9.4	12.5
Mass flow/hr/unit-area reaching last stage	0.032	0.058	0.105
Relative eroding capacity	1.0	1.9	3.6

The erosion problem is seen to be more severe at partial turbine loads than at full load conditions. This effect is probably due to the lower vapor velocities experienced at these conditions.

To summarize, the CERL pictures showed the departure of very large droplets from the stator blades and their subsequent arrival at the rotor blades. These droplets were large enough, ~ 400 μ, to cause considerable damage. However, the large sizes observed were probably a result of the poor blade geometry, which produced sizable wakes and secondary flow. With better blade design and/or wider spacing, the droplet size in this turbine could probably be reduced to ~ 100 μ. Design programs are available that are capable of producing good aerodynamic profiles in a wet-vapor turbine and, thereby, reduce erosion problems. Prediction of the arriving droplet size and optimum blade spacing can probably be accomplished; however, it will require knowledge of the wake characteristics and an analysis of the shedding phenomena in order to use existing breakup analyses.

V. LIQUID IMPACT

The pressures generated by liquid impact and the duration and area of application have been the subjects of considerable analysis and experimentation by the group at Cambridge. According to Bowden and Field, the peak pressure for impact of either a spherical or cylindrical liquid mass on an incompressible solid surface is given by the *water hammer* relation:

$$p = \rho c v$$

where p is pressure, ρ is liquid density, c is the speed of sound in the liquid, and v is impact velocity. This relation is based on the elastic compression of the liquid and on the assumption that no particle velocity is imparted to the fluid until the pressure release wave arrives from the liquid boundary. This result differs from that of Engel (Ref. 8) who assumes a particle velocity to exist immediately upon impact and obtains the expression

$$p = \alpha \rho c v$$

where $\alpha = 0.39$ for water on aluminum.

The former equation used with the impacting jet or droplet area yields approximately the value of peak impact load. This load was measured with a piezoelectric load cell at Cambridge. For these experiments, an average pressure of 134,000 psi was measured vs 153,500 psi predicted by the first relation (Ref. 9). It therefore appears that use of the Cambridge relation is preferred on the basis of experimental results and the fact that it predicts the more conservative value of impact pressure.

Pearson, at Marchwood Laboratory, pointed out that serious errors may result if the values of ρ and c are not corrected for pressure. For example, an impact velocity of 1000 ft/sec yields a predicted pressure of 30 tons/in.^{2} without pressure corrections. With the proper corrections, a pressure of 40 tons/in.^{2} would be predicted. As a result of these compressibility effects, the pressure is proportional to $V^{1.4}$, instead of to V.

Part of the problem of erosion is that the pressures predicted at the lower-impact velocities producing material loss are lower than the yield or fatigue strengths of materials.

The possibility of local high pressures being produced by cavitation in the impact process has been suggested previously (Ref. 10). Photographs have been taken at Cambridge that show extensive cavitation behind the reflected compression wave from a free-liquid surface. Figure 5 shows this behavior schematically. Since the local stresses from a collapsing bubble can be several times the stress from the original liquid impact, this is a possible mechanism to start local surface yielding in *multiple-impact* erosion (see Section VI). This may be particularly significant since Jolliffe has noted that the initial pits in erosion specimens have a smooth, melted appearance with crater lips, as though material flow were present.

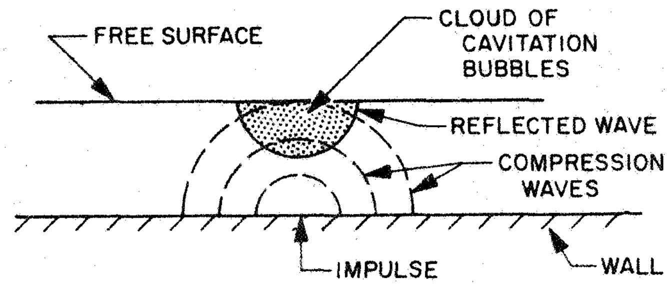


Fig. 5. Schematic of cavitation induced by pressure release wave (after G. P. Thomas, Ref. 11)

The work on micro-jets (Ref. 11) at Cambridge has also identified a phenomenon in which impact pressures greater than $\rho c v$ for the bulk liquid can occur. Velocities are observed for these fine liquid structures which range from 2 to 3 times that of the impacting droplet. The jets can occur either in the form of spike leading the main droplet or as a transverse flow after impact of a spherical droplet (as previously noted by Engel). Central pits have been observed in single-impact craters, which are obviously a consequence of the impact of these high velocity jets (Ref. 11).

Both the duration and the area of application of the peak impact pressure are important to material removal. The duration is usually taken to be the time required for the pressure release wave to arrive at the center of impact for the liquid column or droplet. Thus, the size of the impacting liquid has a definite effect on its erosive properties. Hobbs, for instance, has determined that the damage is proportional to diam^2. This would be expected because of the combined effect of increased duration and impact area.

VI. MATERIAL REMOVAL

A. Removal Mechanisms

The mechanism of material removal for multiple impacts is not well understood. However, the basic experiments at Cambridge and CERL have shed some light on the problem. In both of these investigations, specimens are subjected to low-velocity impacts and periodically examined to ascertain changes in the material. As described elsewhere (Ref. 12), resulting damage appears in several successive steps:

1. Small depressions are formed in the surface without material removal.
2. Grain boundaries become more pronounced; whether this is caused by slip, corrosion, or grooving is not known.
3. Small pits and craters are formed; usually in the depressions noted. Still no weight loss is measurable at this stage of damage.
4. Removal of metal occurs in the pits by tearing, in ductile metals, or cracking, in more brittle metals. At this stage, weight loss is measurable.

The depressions formed were independent of surface treatment. The population was the same for single crystals or polycrystalline materials. These depressions occur at values of impact pressure much below the yield or fatigue strength of the materials tested. For example, depression in copper occurred at velocities of 100 ft/sec, which yield a predicted stress of $\rho c v = 5750$ psi. This can be compared to the yield stress of 21,500 psi or to the fatigue strength of 11,000 psi. The reason for this behavior is believed to be local defects in the material, rather than the occurrence of impact pressures higher than those predicted. Support for this point of view was presented by Thomas, who conducted an experiment in which a surface was subjected to cyclic hydrostatic pressures of the same magnitude as the predicted impact stresses. The appearance of the surface after about 5000 cycles was identical to that of the surfaces subjected to liquid impact. The dimpled appearance has, also, been observed by Hobbs on aluminum walls subjected to cavitation.

The work of Jolliffe has, also, supported the conclusion that material flaws may be responsible for the initiation of erosion. He has observed local yielding at stresses significantly below the average yield strength. The use of chemical etch pit techniques on lithium fluoride single crystals has revealed that single-impact damage occurs on a crystalline scale at the lowest velocities tested (~ 200 ft/sec). This result, together with the Cambridge work, tends to refute the concept of *threshold velocity* below which no damage occurs.

The pits that occur after observation of grain boundary grooving have no particular orientation. Jolliffe has observed that there is a tendency for these pits to start in the vicinity of triple intersections. A melted type of appearance is observed with a crater lip and very clean surfaces. For these reasons the mechanics of formation may be somewhat different from those for the depressions, although Thomas says they are direct extensions of the depressions. The possibility was suggested that some type of cavitation phenomenon, corrosion fatigue or adiabatic compression effects, may be responsible for initiation of these pits. It seems clear, however, that the initial depressions are necessary before development of the pits occurs. They may be due simply to the stress concentration resulting from progressive dislocations of defects in the material.

Material removal occurs in the pits. For the case of brittle metals, cracks propogate from the bottom of the pit. When they meet, particles of material are lost (see Fig. 6). The cracking, which is apparently independent of the direction of impact, may be either intergranular or transgranular. In ductile materials, removal is accomplished by tearing, and a rounded pit is formed. The erosion pits produced have a very large ratio of depth to width. Figure 6 is a schematic representation of a heavily eroded structure.

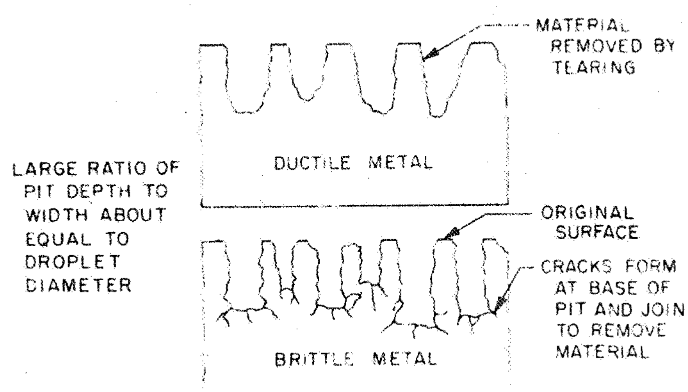


Fig. 6. Typical appearance of erosion test specimens at Marchwood Laboratory

In the specimens at Marchwood, the original surface was seen on some peaks when the depth of material removal was as high as 1/16 in. The peaks apparently remain because as the impact area becomes smaller, the duration of the application of the peak impact pressure becomes very short. For example, it has been observed at CERL that when pins are tested in jets the erosion rate is much smaller than it is for plane surfaces.

B. Experimental Results

Several experimental results have been obtained that furnish information on the rate of weight loss for multiple-impact erosion. These experiments are not directly applicable to liquid metal erosion because of differences in such characteristics as fluid acoustic properties, material properties, temperature, and the corrosive nature of the fluid. However, general trends are indicated that may prove useful in turbine design.

One of the most significant aspects of these tests results is the large scatter of data occurring. Pearson, at Marchwood, has conducted tests where material specimens are mounted on rotor arms and passed through water droplets. Impact velocities were varied from 400 to 1000 ft/sec and drop size from 350 to 1000 μ. For identical specimens —machined from the same piece of material, mounted on opposite arms, and tested at the same time—there was a difference in weight loss of as much as 50%. This result emphasizes the statistical nature of the physical processes involved. It also means that any analytical model for prediction of turbine erosion would, at best, have a spread of about 50% around the actual weight loss, and furthermore, this value would be possible only if droplet size, frequency, velocity, and impact angle were accurately predicted. If the uncertainties in predicting the droplet spectrum are taken into account, together with uncertainties in predicted weight loss for materials and fluids different from those tested, then the best estimate could be as much as 100% from the actual value.

Erosion results obtained by Pearson were expressed in the equation:

$$\frac{dM}{dW_{max}} = K(V \sin\theta - V_c)^n \operatorname{cosec}\theta$$

where

$\frac{dM}{dW_{max}}$ = weight loss during initial steady period of erosion

K, n, V_c = constants which must be empirically determined for each material

θ = angle of impact

V = velocity of impact

For the case of a 13%-chromium stainless steel, the velocity constant V_c was found to be 390 ft/sec. The power of the velocity was 2.6. This result differs from that of Hobbs, who finds the exponent of velocity to be 4.0. Pearson states that, as a general rule, the *pcv* stress corresponding to his *critical velocity* seemed to be about 1/2 the fatigue strength for iron-based alloys and about equal to it for cobalt-based alloys. His results show increasing losses with increasing droplet diameters, except for some anomalous results at the lowest diameters. In general, the pit width on the Marchwood erosion samples showed a close correspondence to the droplet diameter tested. Aluminum-ceramic whisker composites were tested, but nothing remained except the whiskers.

Pearson believes fatigue strength is more important than hardness as an indication of erosion resistance. Part of the reason for his position is related to the fabricability of blading. Also, very hard materials tend to fail catastrophically; this was shown by the spalling of some of his test specimens. A material composed of 50% TiC and 50% TiB_2 with a Vickers hardness of 2000 was very erosion resistant but exhibited spalling. The spalling may have been due to vibration from the rotor, however, so this material may be suitable for static applications. Hobbs believes hardness to be most important in determining the length of the incubation period, or time of zero weight loss. He maintains that extending this period by increasing hardness may be the best approach to erosion resistance. He feels fatigue strength is an important property primarily when the material is already failing. Hobbs has used hardness to correlate his erosion test data and has obtained very consistent results.

Two outstanding exceptions to Hobbs' data correlation are aluminum bronze and stellite, both of which exhibit superior erosion resistance to materials of the same hardness. Both he and Pearson believe that the difference is possibly related to the combination of a ductile matrix and finely dispersed hard phase which occurs in both of these materials. They reason that the presence of the hard phase may limit the initial deformation of the ductile phase, which was observed during the incubation period by Cambridge and CERL. On this basis, it would appear that the microstructure of alloys currently being developed for possible use in liquid metal turbines should be an important parameter in erosion resistance.

One of the erosion-rate curves generated by Hobbs is given in Fig. 7. He interprets his data as an incubation period followed by an initial high rate and then a lower steady-state rate. However, as can be seen, the curve drawn through the data is only one of several possible interpretations. Also, the test duration was not sufficient to determine if the final steady-state value exists or if the erosion rate may still fluctuate, as in Heymann's model (Ref. 13). Hobbs concludes that the first steady-state zone is the important characteristic of the material. Further, he finds that this zone extends over a constant volume of material removed, as in Fig. 8. The decline toward a constant lower rate begins at about the same value of material removed or penetration depth.

The curves shown were obtained for different materials exposed to the same jet velocity and diameter. As previously discussed by Heymann, this result emphasizes the dependency of erosion rate on the surface state.

Experiments at Cambridge have shown two ways in which alteration of the surface have decreased the erosion

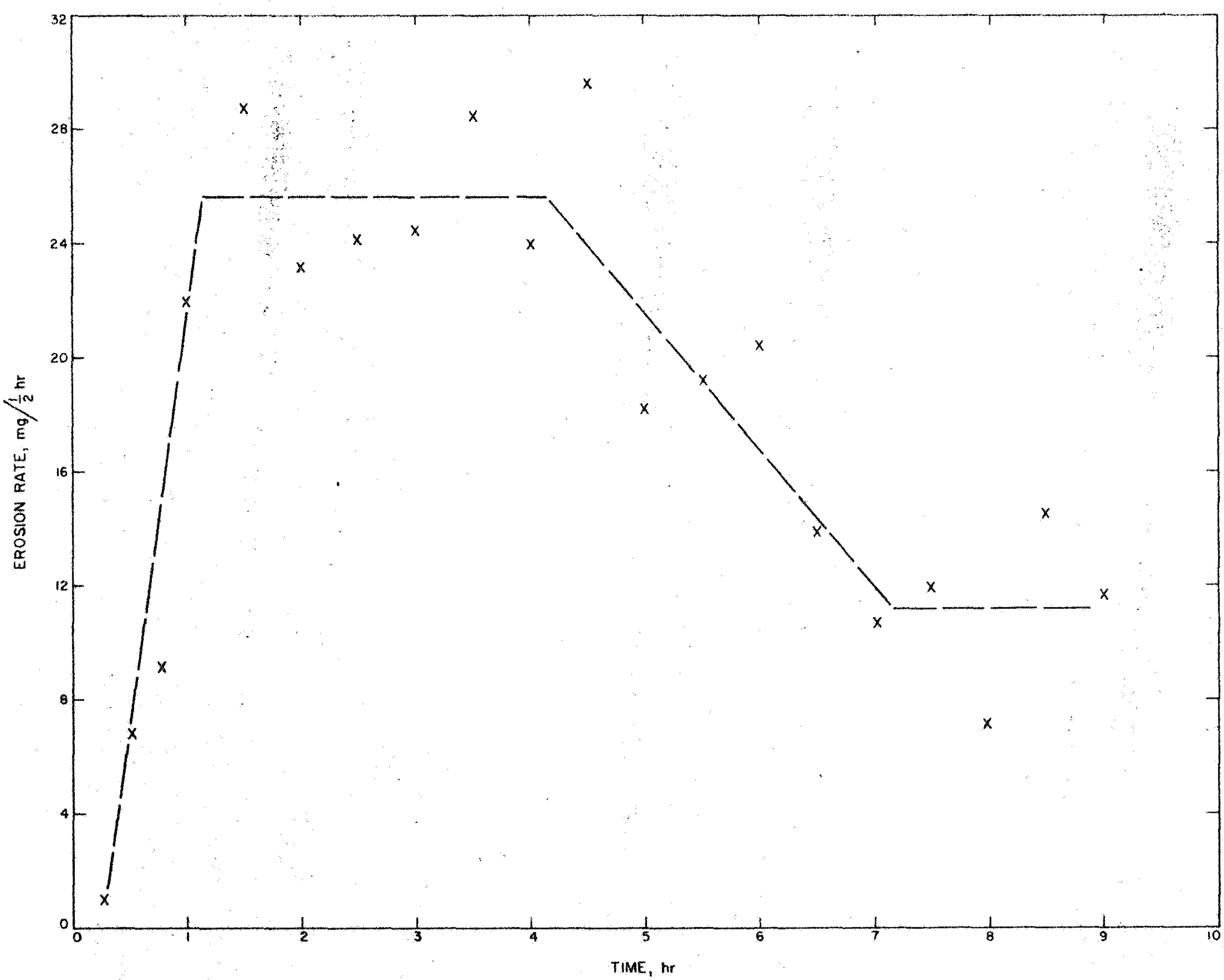


Fig. 7. Erosion rate vs time for a typical stainless steel specimen (from J. M. Hobbs)

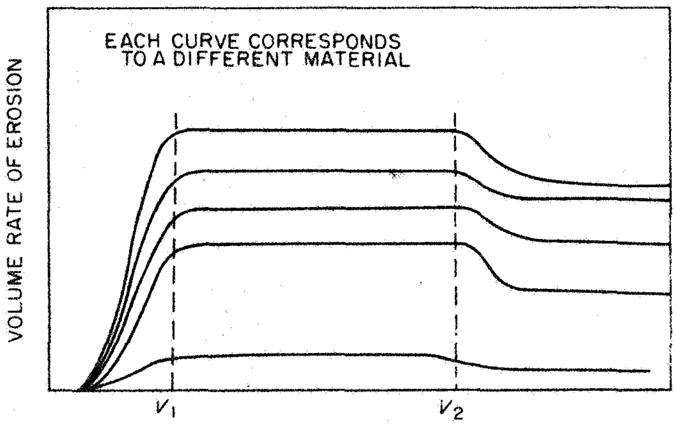


Fig. 8. Influence of total material volume loss on erosion rate (after J. M. Hobbs)

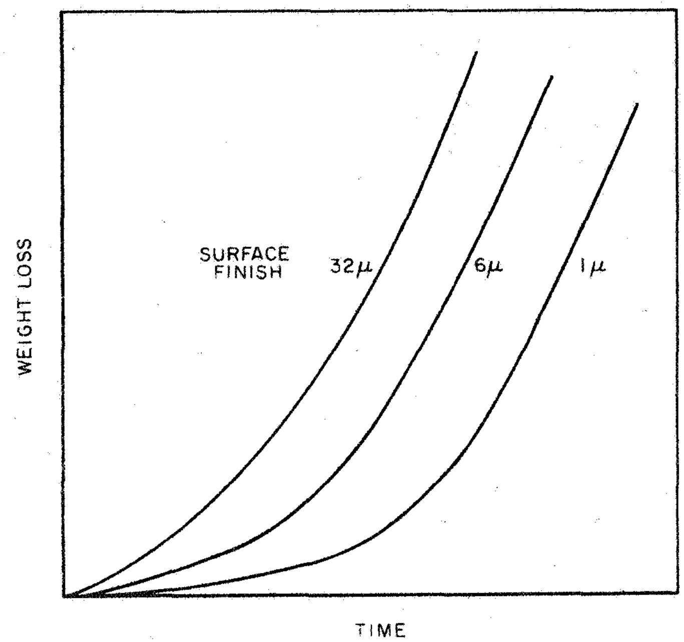


Fig. 9. Influence of surface finish on weight loss (after J. M. Hobbs)

rate. First, in the tests that Field conducted with oil films on surfaces the erosion was shown to be reduced by an order of magnitude. He attributes this result to the fact that the oil film covers surface irregularities and, thereby, reduces the tearing action of the transverse flow. It should be noted that no effect was observed by DeCorso for single-impact experiments (Ref. 14). However, liquid film protection has also been demonstrated in multiple-impact experiments at JPL (Ref. 15) and by Hobbs. The high values of surface tension and wettability of liquid metals may provide a similar type of protection for turbine blades in these media.

The other effect found by Field was that chemical etching of surfaces increases the resistance to both single and multiple impact. This effect was also found by Hobbs, as illustrated in the curves of Fig. 9. Notice that the better surface finish delayed the inception of erosion, but once it started, the same rate of weight loss occurred for all specimens. The reason advanced by Field for this behavior was that the etching process rounded the corners in surface imperfections which, otherwise, would provide large stress-risers for liquid impact pressures. The formation of pits is therefore delayed. However, once the pits are formed, material removal occurs within them, and the weight loss is independent of the initial surface treatment.

To summarize, the work in Great Britain has provided a good deal of information on basic mechanisms of erosion. In particular, this work has shown conclusively that it is possible for a metal to undergo local yielding under impact or hydrostatic stresses that are many times lower than the average stress required to cause yield, or fatigue failure. The observed behavior may suggest the reason for the binary phase alloys of stellite and aluminum bronze exhibiting superior erosion resistance to that of normal alloys. This result also suggests that physically similar refractory metal alloys should be evaluated for use in liquid metal turbines. Good correlations of weight loss vs material properties, as well as liquid impact parameters, have been developed at Marchwood and National Engineering Laboratory (NEL); these may provide bases for predicting erosion behavior for different materials and fluids. The random nature of the removal process is responsible for a good deal of variation in all of the results noted thus far and, undoubtedly, will limit the accuracy of any prediction method.

VII. EXPERIMENTAL APPARATUS

The most significant advance in erosion instrumentation is the photographic technique developed by CERL for obtaining films of moisture in operating turbines. The initial apparatus developed used conventional optics and light sources. Two major problem areas were encountered —fogging of the periscope lens (Fig. 10) and reflections from fog-like droplets. The former was solved by blowing air across the lens and the latter by moving the light source to obtain satisfactory transmission.

Christie provided a very complete description of the apparatus. Figure 10 shows the periscope that was developed for the CERL work; it has a tungsten light on a swivel at the remote end. Christie said that a tilting mirror, mounted behind a pressure-tight glass window, adjacent to the light source, allows the direction of view to be turned at right angles to the main body of the periscope. The lens in the tube brings the image reflected down the tube to focus at the focal plane of either a camera or a microscope eyepiece. A flexible seal at the outer casing of the turbine permits the periscope to scan along a single blade; and by raising or lowering the inner end of the periscope, several adjacent nozzle blades can be examined.

The necessity for backlighting the droplets to obtain satisfactory photographs is pointed out by Christie. This is achieved by use of a quartz-rod light guide to transmit light from an external source into the clearance space between the last stage stator and rotor. The external source used was a 20-J xenon flash. A mirror and lens was used to direct the light behind the water droplets. The light pulses from the xenon flash were synchronized with the camera to give a maximum of 25 flashes/sec with a pulse duration of 4 μsec.

The high-velocity wet steam flowing through the last low-pressure stage was said to resemble a thick fog, which caused a good deal of light scattering. A 200-w quartz-iodine lamp focused on the blade provided a light level of only 1 to 2 ft-c at the film plane.

Later work at CERL has been directed toward using a laser light source. The reasons for use of a laser are it provides a higher intensity and shorter pulses than does the xenon flash, thereby enabling much smaller droplets, traveling at higher velocities, to be photographed. CERL had just obtained some still photographs of droplets with the laser; there was ample intensity to penetrate the fog-like droplets. The laser beam was introduced through a polished hollow tube with normal optics. A ground-end prism was used to break up the coherency of the beam.

Another innovation being used at CERL to measure droplet size is an electrostatic probe. This device is a charged wire that is discharged when impacted by a droplet. Since droplets usually have a charge, the unit has to be operated at two different potentials to subtract out droplet charges. The calibrations for this device appeared to be very linear. The circuit is shown schematically in Fig. 12, together with the typical discharge curve. The characteristic decay time of ~ 50 μsec fixes the maximum counting rate to about 20,000 droplets/sec. This instrument is described in detail in Ref. 16.

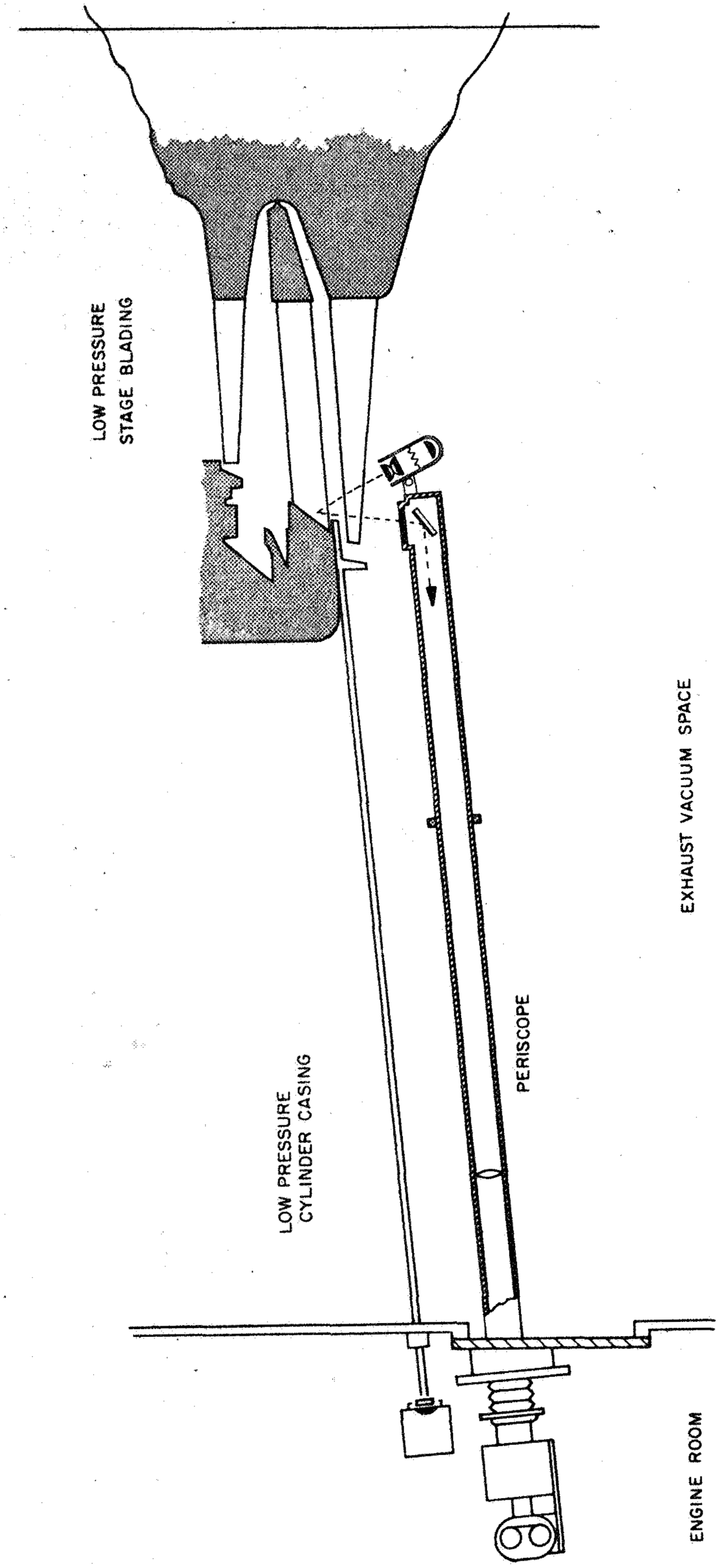


Fig. 10. Installation of periscope in turbine (after CERL)

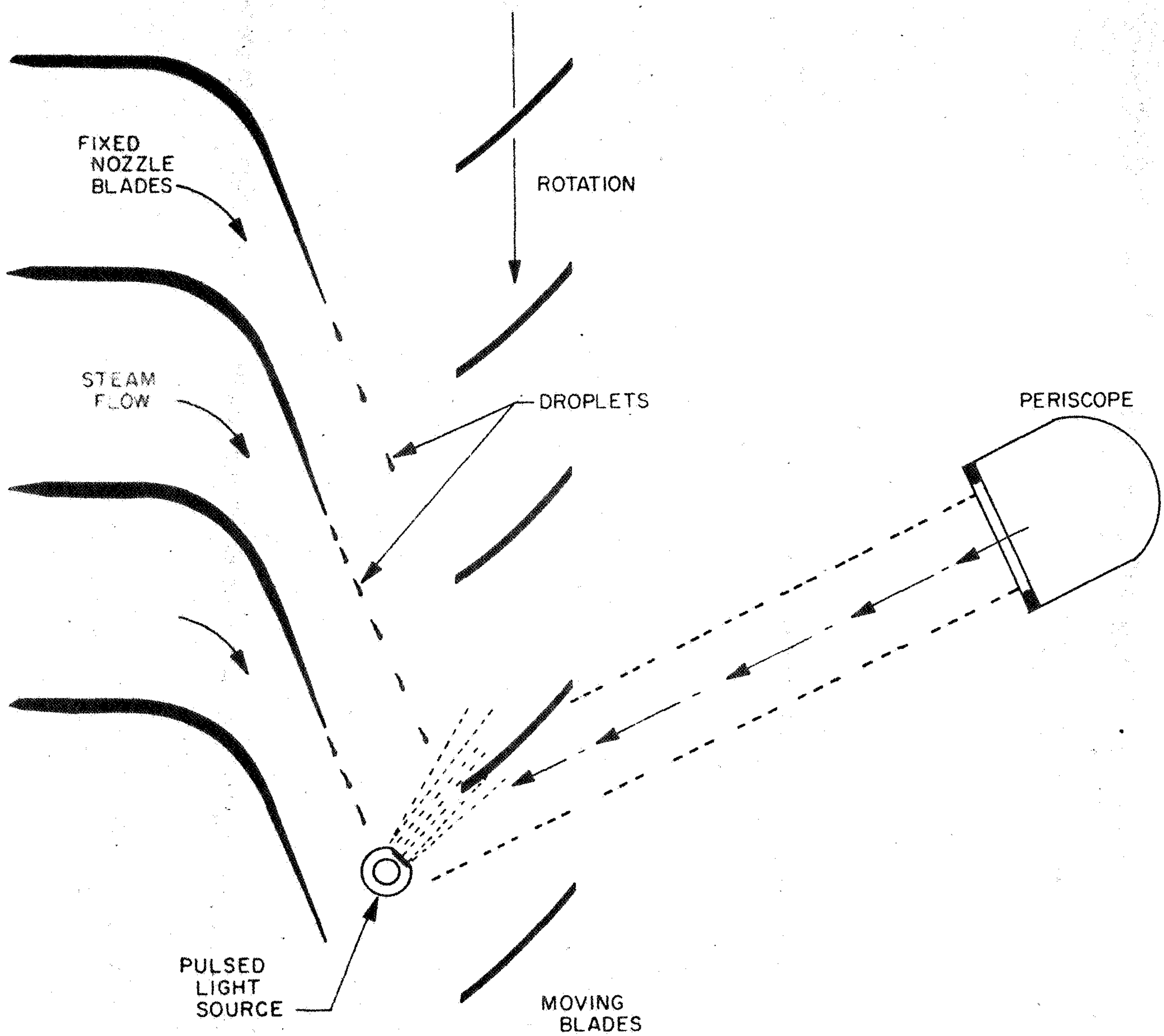


Fig. 11. Geometry of optics and turbine blading (after CERL)

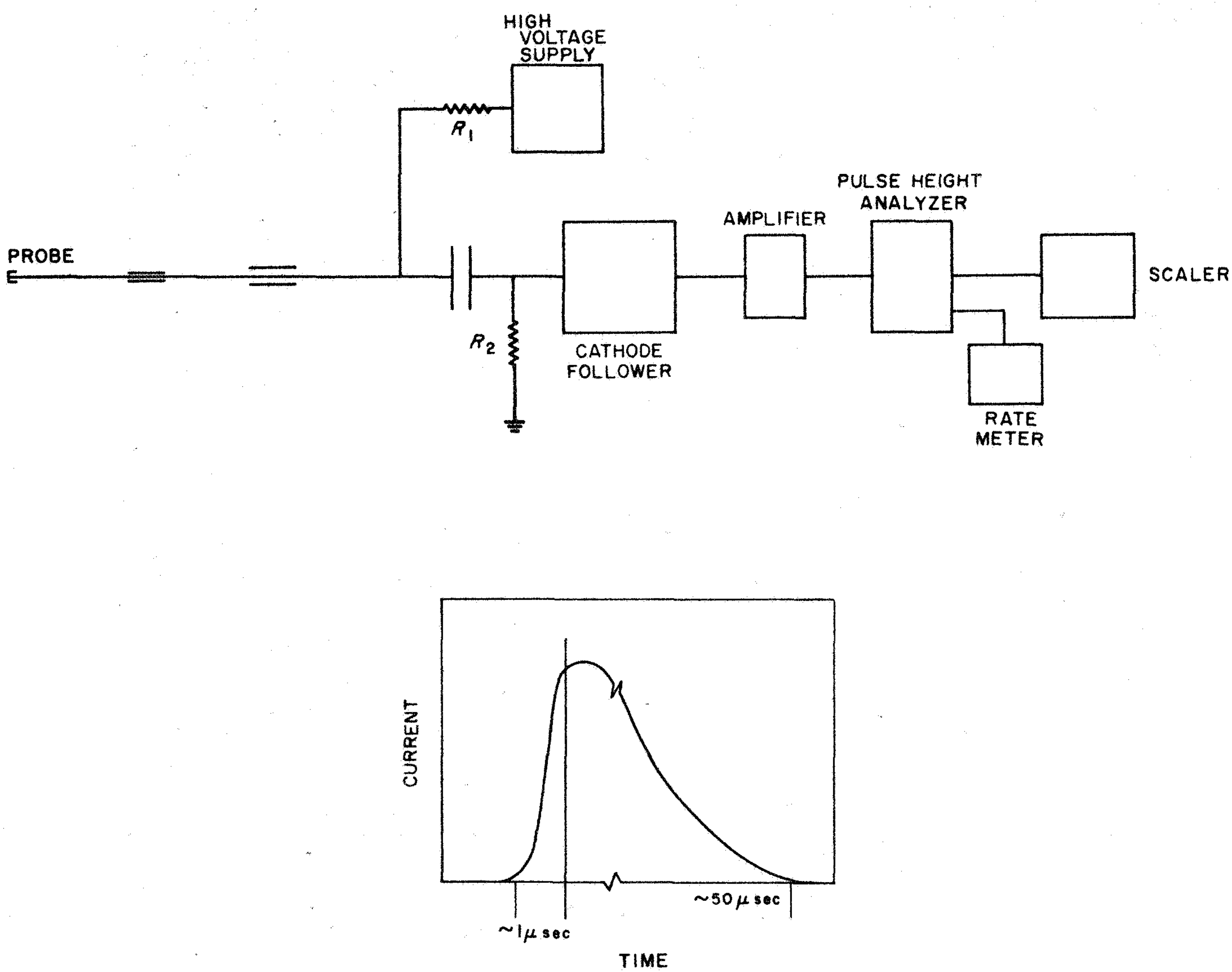


Fig. 12. Schematic of electrostatic droplet probe circuit and typical pulse (after CERL)

VIII. CONCLUSIONS

Research on turbine erosion, including its associated phenomena, is quite advanced in Great Britain. This appears to be due mainly to an early recognition of the problem and a decision to attack it on a basic, rather than applied, level. While the equipment and facilities appear to be less sophisticated than those available in the United States, a good deal of basic thought and ingenuity has been applied to the equipment available, and meaningful tests have been conducted.

The results of work with steam in Great Britain cannot be directly applied to the problem of erosion in liquid metal turbines. However, the following general conclusions were formed as a result of information acquired on this visit:

1. Existing condensation theory is probably adequate for liquid metals. However, a definitive experiment is lacking, and accurate data on surface tension is needed.

2. Location of the reversion point in a region of high pressure gradient is a promising technique to reduce erosion.

3. Gyarmathy's treatment of collection should be adequate for liquid metals; however, a definitive steam test is needed to choose between his model and Gardner's.

4. The flow phenomena that dominate droplet shedding and breakup are the occurrences of wakes and secondary flows. The shedding phenomenon is repeatable and, from the CERL films, appears amenable to analysis. Increases in the stator-rotor gap should increase breakup, resulting in decreased erosion.

5. The area average peak-impact pressures are given by the water hammer pressure $\rho c v$. However, local pressures can result from Munroe jets, cavitation, or adiabatic compression which exceed this value by a factor of 2 to 3 or greater. The duration of the applied pressure is proportional to the diameter of the impacting droplet or jet.

6. The initial damage in multiple-impact erosion is due to local weak areas in the material which yield under stresses much lower than the bulk yield strength, or fatigue strength. This stage of damage appears to be reduced by using materials with a very hard phase that is finely dispersed in a ductile matrix. Therefore, the physical micro-structure is an important parameter to be investigated in the development of erosion-resistant alloys for liquid metals.

7. The extent of the influence of corrosion on material removal is not yet understood for water. Some investigators feel it may play an important role, because of the high flow velocities. If this is true, corrosion effects should be very pronounced with liquid metals.

8. Some mechanical damage reduction may occur with liquid metals because of the high degree of wetting and the subsequent surface film adherence.

9. Current correlations of erosion rate for water vs material hardness or fatigue strength may provide a crude basis for estimating mechanical liquid-metal erosion. However, liquid-metal multiple-impact tests on refractory metal specimens must be obtained before even a moderate degree of confidence can be placed in any erosion model.

10. The statistical behavior of the erosion process is such that a great many specimens must be tested for a given set of parameters to obtain a satisfactory average. The spread of the resulting data is such that an erosion model can probably provide a designer only with an erosion estimate which is valid to within a factor of 2 or 3.

11. The optical measurements in operating turbines and cascades made at CERL appear to be the result of straightforward techniques. Application of these techniques to small geometries with steam appears feasible; the possibility also exists for their eventual application to liquid metals through the use of sapphire windows. The electrostatic probe developed at CERL can be applied directly to liquid metal turbines to measure droplet size.

REFERENCES

1. Gyarmathy, G., "Bases for a Theory for Wet Steam Turbines," Bulletin No. 6 of the Institute for Thermal Turbo-machines in the Federal Technical University, Zurich, 1962.

2. Gyarmathy, G., and Meyer, "Spontane Kondensation," *Ver. Deut. Ingr. Forschungsh*, No. 508, 1965.

3. Katz, J. L., Saltsburg, H., and Reiss, H., *Nucleation in Associated Vapors*, Technical Memorandum No. SCPP-65-32, North American Aviation Science Center, Canoga Park, Calif., May 1965.

4. Gardner, G. C., "Events Leading to Erosion in the Steam Turbine," *Proc. Inst. Mech. Engrs. 178 Part 1*, No. 32, 593-623 (1963-1965).

5. Stahl, William F., *The Development of a New Low Pressure Turbine Design Method and Its Application to an Experimental Low Pressure End*, Engineering Report E-1316, Steam Division, Westinghouse Electric Corp., Lester, Pa., May 1957.

6. Morrell, G., *Critical Conditions for Drop and Jet Shattering*, NASA TN D-677, National Aeronautics and Space Administration, Washington, D.C., February 1961.

7. Bowden, F. P., and Field, J. E., "The Brittle Fracture of Solids by Liquid Impact, by Solid Impact and by Shock," *Proc. Royal Soc. (A)* 282, 331-352 (1964).

8. Engel, O. G., "Note on Particle Velocity in Collisions Between Liquid Drops and Solids," *J. Research Natl. Bur. Standards (A) 64A*, No. 6, (November–December 1960).

9. Brunton, J. H., "Deformation of Solids by Impact of Liquids at High Speeds," *Symposium on Erosion and Cavitation*, Special Technical Publication No. 307, ASTM, 1961.

10. Engel, O. G., "Waterdrop Collisions with Solid Surfaces," *J. Research Natl. Bur. Standards 54*, No. 5 (May 1955).

11. Brunton, J. H., Field, J. E., and Thomas, G. P., "Impact of Liquids on Solids," *The Times Science Review*, No. 57, London (1965).

12. Heymann, F. J., "Report on a Trip to Great Britain to Attend a Symposium and Visit Laboratories Concerned with the Erosion of Solids by Liquid Impact," Steam Division, Westinghouse Electric Corp., Lester, Pa., June 1965.

13. *Basic Investigation of Turbine Erosion Phenomena*, Report No. WANL-PR(DD)-003, First Quarterly Progress Report on Contract NAS 7-390, Astronuclear Laboratory, Westinghouse Electric Corp., Pittsburgh, Pa., September 1965.

14. DeCorso, S. M., and Kothmann, R. E., "Erosion by Liquid Impact," *Symposium on Erosion and Cavitation*, Special Technical Publication No. 307, ASTM, 1961.

15. Elliott, D., et al., "Liquid MHD Power Conversion," *Space Programs Summary No. 37-25, Vol. IV*, Jet Propulsion Laboratory, Pasadena, California, 1964.

16. Gardiner, J. A., "Measurement of the Size Distribution in Water Sprays by an Electrical Method," *Instrument Practice*, 353-356 (April 1964).